An Appraisal of the Range and Reliability of Mean Oxygen Isotopic Values due to the Effect of Cut and Fill Activity During Sedimentation

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Abstract

In this paper I have discussed the meaning of oxygen isotopic ratios and what causes them to vary. These causes included fractionation, temperature changes, and other relevant variables. I also discussed what would make their mean values vary, namely the effects of cut and fill features due to erosion and drifting.

I attempted to measure the effect that cut and fill would have on the mean values by determining a range, a ± variation, of the mean $\delta^{18}O$. This was done by using pit profiles and computing new means which resulted from gaps placed within the profile. These were compared to the original mean value to determine how it varied due to gaps of differing sizes.

These ranges were then combined with a probability distribution of gap sizes to give an average range for each pit. These varied from ± .0425 ^{o}/oo to ± .0694 ^{o}/oo for thicknesses of firn equal to 19 years accumulation in each pit. I discussed some possible reasons for the variations seen in these average ranges from pit to pit, but it appears there is no definitive answer available from the data at hand.

I concluded that the ranges are not significant for paleotemperature determinations. But, they may be important for future studies of the effect of elevation on oxygen isotopic ratios.

<u>Objectives</u>

The purpose of this project is to assess the reliability of mean oxygen isotopic ratios, by calculating the effect that cut and fill at the surface has on these means. These cut and fill features, resulting from erosion and drift, could result in the absence of sections of the strata or the presence of abnormally large deposits of material, that may not be present in sections a short distance away.

To evaluate the influence these factors might have on the computed means, we must find a way to estimate how much the mean would vary with a gap of a given size occurring at any time during the depositional history. This was done by artificially removing given thicknesses of firn at all locations within a profile and then computing a mean for each instance. These were then compared with the original mean, for the pit, to determine the range of possible deviations due to all such gaps. After doing this for gaps of several sizes for each pit, I then plotted these ranges against the the gap size for each of the pit profiles. These curves were then combined with the probability of each size gap to obtain an average range for that pit. This average range then gives us a measure of the reliability of the mean for that pit.

Loss of samples for various reasons have caused large real gaps in some profiles. It was hoped we might use the curve of the range vs. gap to predict how much the mean would vary in such instances. This would allow for the use of these profiles and their computed means with much greater confidence than was possible before.

Importance of Study

We believe that this study is important due to the significance which is being given to the mean of oxygen isotopic ratios. These means are being used to give an indication of the average annual temperatures of the area in the past. Therefore, having some idea of the possible range of such means due to the effects of drift and erosion would be very valuable. There are also studies of how the oxygen isotopic ratios vary with elevation and knowing the reliability of the means would be helpful when designing future experience of this type.

This study might also be important in other areas of geology where the use of profiles similar to those of oxygen isotopic ratios is common. If there is a meaningful variation found here due to erosion and drift, possibly there may be similar effects present in these other types of profiles. This implies that maybe their use should be subjected to closer scrutiny.

Theory and Variables

There are several variable which influence mean oxygen isotopic ratios and their paleoclimatic significance, and I shall attempt to touch on the more important of these. They include fractionation, differing paleoclimatic weather patterns which influence wind directions, changes in the oceanic standard values due to water locked in continental glaciers, and of prime importance to this study, the variation due to drifts and sastrugi.

Oxygen isotopic ratios and their paleoclimatic and subsequent geologic significance stems from the fractionation of ^{18}O and ^{16}O between the vapor and liquid phases of the water molecule. The equilibrium vapor pressures of these different isotopes are inversely proportional to their masses. So that ^{16}O evaporates more readily while ^{18}O condenses more readily. This results in the vapor formed by evaporation of liquid water being enriched in $H_2{}^{16}O$ while the remaining liquid is enriched in $H_2{}^{18}O$.

The oxygen isotopic composition is reported in terms of the $^{18}O/^{16}O$ ratio relative to a standard value called SMOW (Standard Mean Ocean Water), according to the equation:

$$\delta^{18}O = \left[\frac{\left(^{18}O/^{16}O\right) \text{sample} - \left(^{18}O/^{16}O\right) \text{SMOW}}{\left(^{18}O/^{16}O\right) \text{SMOW}} \right] \text{X } 10^3 \ ^o/oo$$

This relationship is such that enrichment of a sample in ^{18}O compared to SMOW gives a positive value while enrichment of the sample is ^{16}O relative to SMOW gives a negative value.

When water evaporates from its source body, in this case the ocean, the vapor is enriched in ^{16}O because of its higher vapor pressure and its tendency to evaporate more readily. This vapor then has a negative $\delta^{18}O$ value. As precipitation occurs from this air mass the liquid formed is enriched in ^{18}O due to its lower vapor pressure and thus the first precipitate will have a $\delta^{18}O$ value similar to that of its source body. But, further removal of ^{18}O from the vapor phase causes the oxygen isotopic ratio to become increasingly more negative as precipitation continues. This effect continues to be compounded so that subsequent precipitation also becomes more negative due to the preferential depletion of the heavier isotope. This effect would suggest that as the air mass moves inland and begins to dump its precipitation the accompanying $\delta^{18}O$ values of snow deposited further along the storm track should become increasingly more negative. This explains why one expects more negative $\delta^{18}O$ values on the interior of the continent than along the coast. This is one influence that researchers hope to measure with the help of mean oxygen isotopic ratios obtained from shallow pits and cores.

This is not however the only influence that governs the $\delta^{18}O$ values. Dansgaard (1964) demonstrated that their was a linear relationship between the $\delta^{18}O$ values of average annual precipitation and the average annual air temperature of the area. This relationship is shown by the equation:

$$\delta^{18}O_m = 0.695\ t - 13.6$$

where t is the average annual surface air temperature in degrees C and $\delta^{18}O_m$ is the annual mean $\delta^{18}O$ value of the precipitation. This is due to the increase in the liquid to vapor fractionation factor with decreasing temperature, so that as the temperature drops the vapor becomes increasingly more depleted in ^{18}O. This results in subsequent precipitation also being depleted in ^{18}O and having an increasingly negative $\delta^{18}O$ value.

The combined effects of temperature and distance from the source body work in conjunction to give increasingly more negative values as one moves inland and to higher latitudes and higher elevations. This effect should then be reflected in the mean $\delta^{18}O$ as the core sites move inland and up onto the interior plateau.

Another variable which could affect the mean $\delta^{18}O$ values, stems from the circulation patterns of the atmosphere. A major change in the direction of the wind carrying the water vapor which is to become precipitation could cause a significant change in the $\delta^{18}O$ values recorded in this precipitation. If, for example, the wind shift were to cause the vapor to travel much farther across the continent before reaching its deposition point the $\delta^{18}O$ values would be significantly more negative than if the air mass had traveled a shorter distance and thus undergone isotopic fractionation for a shorter period of time. Studies on present ice sheets might suggest a way that such changes in the mean values across the whole continent, at one time period, might be determined and used to decipher paleoclimatic changes in the circulation patterns.

The use of mean oxygen isotopic values to suggest changes in climates accompanying continental glaciation has been a major use of such means. But, there may be other changes which have affected the distribution of the different oxygen isotopes at these periods in history. The continental ice sheets could have stored large amounts of ^{16}O as compared to smaller quantities of ^{18}O; thereby, changing the distribution of these isotopes in the worlds ocean, (Faure, 1977). The increased $\delta^{18}O$ of the oceans would have then been reflected in all the $\delta^{18}O$ values recorded in the precipitation at this time, by making them all more positive than if the ocean had been at SMOW. If this did occur it could have caused the temperature change reflected in the means to be less than that which really took place.

The other variable which I wish to discuss does not affect the oxygen isotopic ratios of individual snow crystals, but instead is related to the final accumulation and compaction of this snow into firn. The most influential variable of this type and the one which I am most concerned with in this study is the effect introduced by the drifting of snow.

The erosive power of the winds on the Antarctic Continent are not new to study, they have been investigated extensively by Budd, Dingle, and Radok (1964) and also by Loewe(1970). However, the effect of these winds, and the cut and fill features which they introduce, have not been considered in relation to their influence on oxygen isotopic ratios recorded in the firn.

We believe that drifts and sastrugi may cause a measureable effect on the mean values computed from pit profiles. It has been shown that these cut and fill features are distributed as shown in Figure 1, (Whillans, 1978). If such cut and fill features do occur with this frequency it is reasonable to assume that they will disrupt the continuity of material being finally incorporated into the firn record. Both abnormally large accumulations of material and erosion of previous deposits may result from the action of these drift inducing winds. However, the effect caused by scour and removal of material may be more important here, based on the evidence of earlier studies (Loewe, 1970) showing the large quantity of material being carried off of the continent by wind transport. This material came from the removal of surface deposits by wind action and its loss must influence, to some degree, the final mean value we see in the pit record.

This study does not take into account the possibility that these cut and fill features may occur more often during one season of the year than another. It seems likely that the winds capable of large cut and fill features might occur more often during the winter months. And also the higher resistance of summer crusts to erosion suggests that these mechanisms may be of more importance during winter than during summer. These factors would weight the mean toward the positive more heavily than might be expected from the ranges discussed later.

Data Source

The data used in this study came from three pits dug in Marie Byrd Land, Antarctica in December 1973 and January 1974, by an expedition led by Ian Whillens. Samples of two centimeters thickness were taken all the way down the pit wall and these were sent to The Geophysical Isotope Laboratory, University of Copenhagen, Denmark, for measurement. The oxygen isotopic ratios and the beta emission levels were measured for each of these samples. The oxygen isotopic ratios were then plotted versus the depth of sample to give a profile for each pit, Figures 1,2, and 3. The 1954/1955 and the 1964/1965 levels were determined for each of these pit profiles using the beta emission levels. These pit profiles are the data bases used for all further calculations carried out in this study.

Methods and Calculations

One of the problems concerning me in this study was the presence of gaps in the oxygen isotopic profile due to the loss of material during drilling, and in one or two instances loss of samples in transport. To fill in these gaps I attempted to compute a running mean of that portion of the profile and use this to fill in these gaps. This method proved successful only for small gaps, but was not satisfactory for gaps exceeding 15 cm. This was not unexpected however, this much firn could well represent a full season's accumulation and its loss would have a marked effect on the mean. It appears that use of the ranges shown in Figures 5, 6, and 7, would be a more reliable method of predicting the errors introduced by the loss of such data.

The major portion of this project was involved with invoking gaps artificially on a profile and identifying the effect that these had on the computed means. These gaps varied from 2 cm through 40 cm because this was the variation found in surface relief in this area, as seen in Figure 4, (Whillans, 1978).

I invoked a gap of given thickness at each possible location within the profile and calculated a new mean each time. Every one of these means was then compared to the original to determine the difference. These variations were then plotted, showing their distribution on either side of the mean, Figures 8a and 8b. From this distribution I then determined the range above or below the original mean. Therefore, range is defined as the possible variation in the mean, this being in either a plus or minus direction. The appropriate notation for mean would then be written as:

$$\text{Mean} \pm \text{Range } ^{o}/oo.$$

Ranges were calculated, in this manner, for several different sized gaps for each pit. These ranges were then plotted against the gap size, resulting in the curves of Figures 5,6, and 7. These curves are drawn through the origin because there can be no variation in the mean when there are no gaps. These curves are also seen to reach a plateau in the vicinity of gaps of 30 to 40 centimeters. This can be explained by the fact that as the gap increases beyond that size it approaches the value of the average annual accumulation for these pits. As the material from a whole year's accumulation is excluded the large variations in the mean tend to be nullified. This is because both summer and winter snow layers are missing and they cancel out each others effect on the mean.

I have attempted to combine the probability distribution and the range curves in two different manners. The first method is a graphical approach resulting in Range-Probability Curves, Figures 9,10, and 11. These enable one to ascertain the percent probability of any certain range occurring or to determine the maximum range which could occur in a given percent of all cases. For example, there is a 90 percent probability that the range is less than or equal to the following figures:

Pit 2803, less than or equal to ± .085 °/oo

Pit 104 , less than or equal to ± .100 °/oo

Pit 2003, less than or equal to ± .140 °/oo

The other method of combining these is a mathematical approach, by which I have determined a parameter, which I shall call average range. I multiplied the percent probability of a given gap by the range resulting from such a gap. I did this for each increment in the probability curve and then summed these values and divided by 100 to obtain the average range. To determine how this average range was affected by the thickness of the profile being evaluated, I carried out this calculation for the pit section 1973/1974 thru 1954/1955, and also for the 1973/1974 thru 1964/1965 pit section. This proved that the range varies inversely with the thickness of the section being considered. Such that:

$$R_a = \frac{R_b N_b}{N_a}$$

where R is average range and N is the thickness of firn for any two sample sections within the same pit. This suggests that such ranges are more important when considering the accumulation of only a few years, but that they become negligible as the size of the section being considered becomes large.

The calculations discussed give the following means and average ranges for a 19 year accumulation of firn:

Pit 104 Mean = $-33.6968 \pm .0555\ ^{o}/oo$

Pit 2803 Mean = $-33.8054 \pm .0425\ ^{o}/oo$

Pit 2003 Mean = $-33.9346 \pm .0694\ ^{o}/oo$

The reasons for these differences in ranges will be discussed further in the next section.

It is interesting to note that the average ranges correspond, in each case, to a value on the Range-Probability Curve which represents a maximum range for 63 percent of all cases. The only significance this has, is that one can determine this average range directly from the Range-Probability Curve and thus save extensive calculation. Even though, I shall continue to use these average ranges though-out the remainder of this study, there may be some merit to using ranges which encompass a greater percentage of the possible cases, such as those seen earlier for 90 percent probability.

Discussion

This method of calculation has made the assumption that only one gap occurs within a profile at any one time. And this, as one might suppose, is not likely to occur in nature. However, I feel that this has been compensated for by combination of the curves with the probability curve, which weights the range of each gap size according to the number of times that it might be expected to occur.

There may be some variation of the average range due to seasonal effects. The probability curve used was determined from observations of summer snow surfaces only. In light of the increased frequency of drift inducing winds during the winter months (Loewe, 1970), I suspect that the frequency of larger cut and fill features may increase during the winter season. If this is true the average range could very well be double that computed here. Future research in this direction could therefore increase the viability of such ranges by considering the effects of such seasonal fluctuations.

The computed average ranges are seen to vary somewhat from one pit to another. Although the accumulation rates vary from pit to pit this effect is probably not the only cause for such variation. I believe that the major factor involved here may be the position of the pit relative to the surrounding topography. Pit 2003 which had the largest range had an accumulation rate which was larger than that for Pit 2803, but much smaller than that for Pit 104. However, Pit 2003 was near the crest of a hill suggesting that it might undergo periods of erosion and accumulation that are more extreme than those at the bottom of the hill, such as affected Pit 2803. This is supported by the presence of several years with extreme accumulations, almost twice the average rate, seen in the profile of Pit 2003, Figure 1. So we might assume that the erratic nature of accumulations present near the top of such a hill is reflected in the profile and the ranges computed from that profile. If this is true it would seem to support the argument that cut and fill does indeed affect the computed mean significantly in certain cases. But, since I can not be sure exactly what has caused this difference in ranges between pits; I can only speculate as to the significance of this variation, until further proof is available.

Conclusions

The average ranges calculated lie between values of ± 0.0425 °/oo and ± 0.0694 °/oo for accumulations of 19 years. Since they are inversely related to the total thickness, it seems reasonable to assume that such variations would indeed be negligible when dealing with paleoclimatic effects over an extended period of time. However, when computing means for smaller sets of data, such as 10 or 20 years worth of accumulation, these ranges may be important.

These ranges are of more significance when dealing with the correlation of the mean $\delta^{18}O$ values to elevation. Since there is not much known about this effect it is important to consider the possible variation in mean values in such studies. This is most important in the planning of future pits, since for their information to be significant they must be spaced sufficiently far apart so that the ranges of their means do not overlap. For example, Pit 2003 with a mean of -33.9346 ± .0694 °/oo and Pit 2803 with a mean of -33.8054 ± .0435 °/oo may be to close together to be of any use, since their ranges nearly overlap. This would be a worthwhile consideration to make whenever planning future expeditions to collect such data.

Variations in mean values of the order of magnitude seen here do not appear to be of much importance when using them to compute mean annual temperatures. However, these represent only normal conditions and do not represent extreme cases where cut and fill features may vary widely from season to season. This study does not deny the possibility of such effects, but it appears that in most cases these variations are not of major concern in the use of oxygen isotopic means for paleoclimatic determinations. However, as we have noted these ranges do become more important when considering the elevation effect on the mean, and their consequence should not be overlooked in planning such studies.

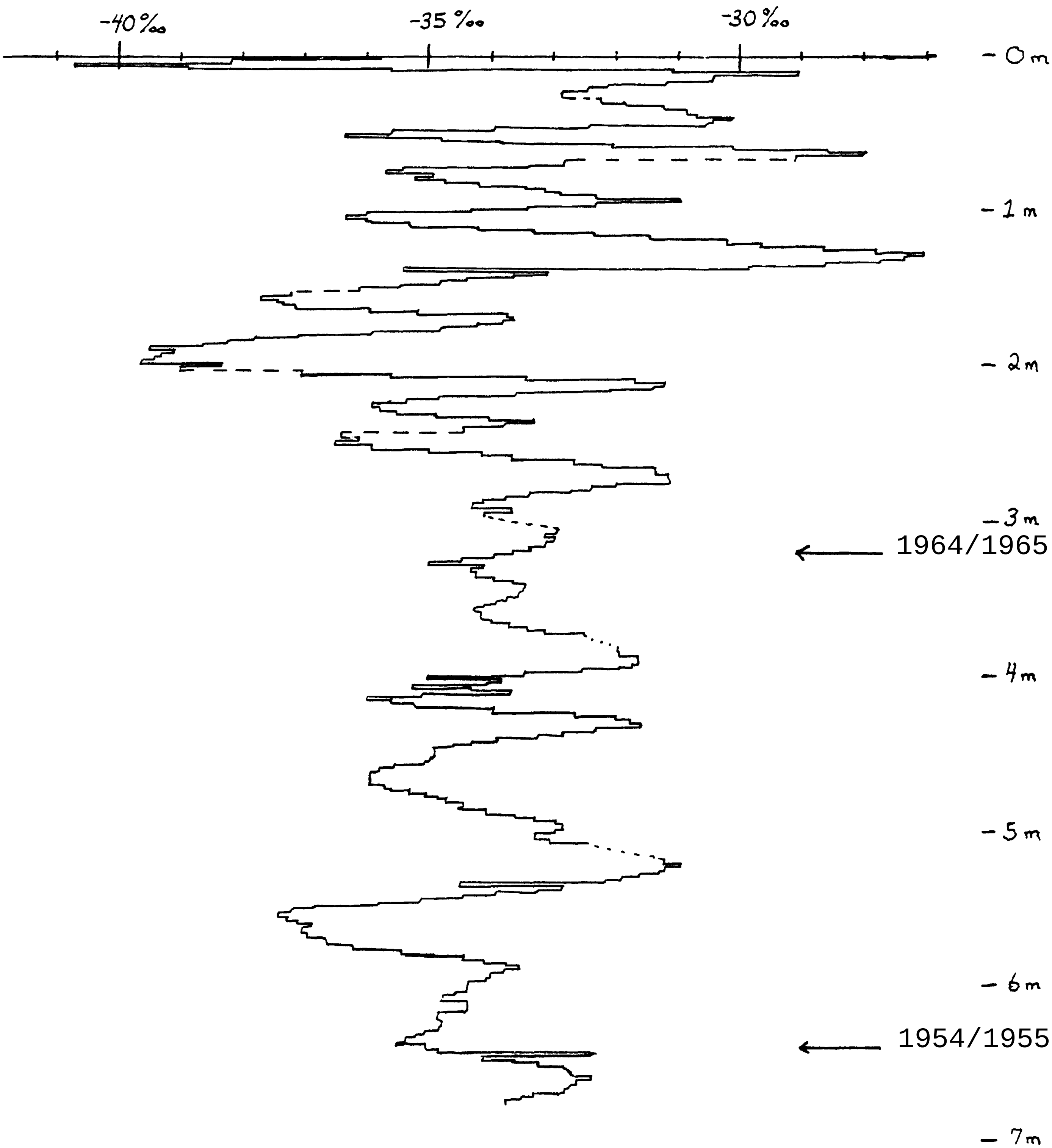

Figure 1. Profile of <u>Pit 2003</u>

Mean = -33.9346 ± .0694 ‰

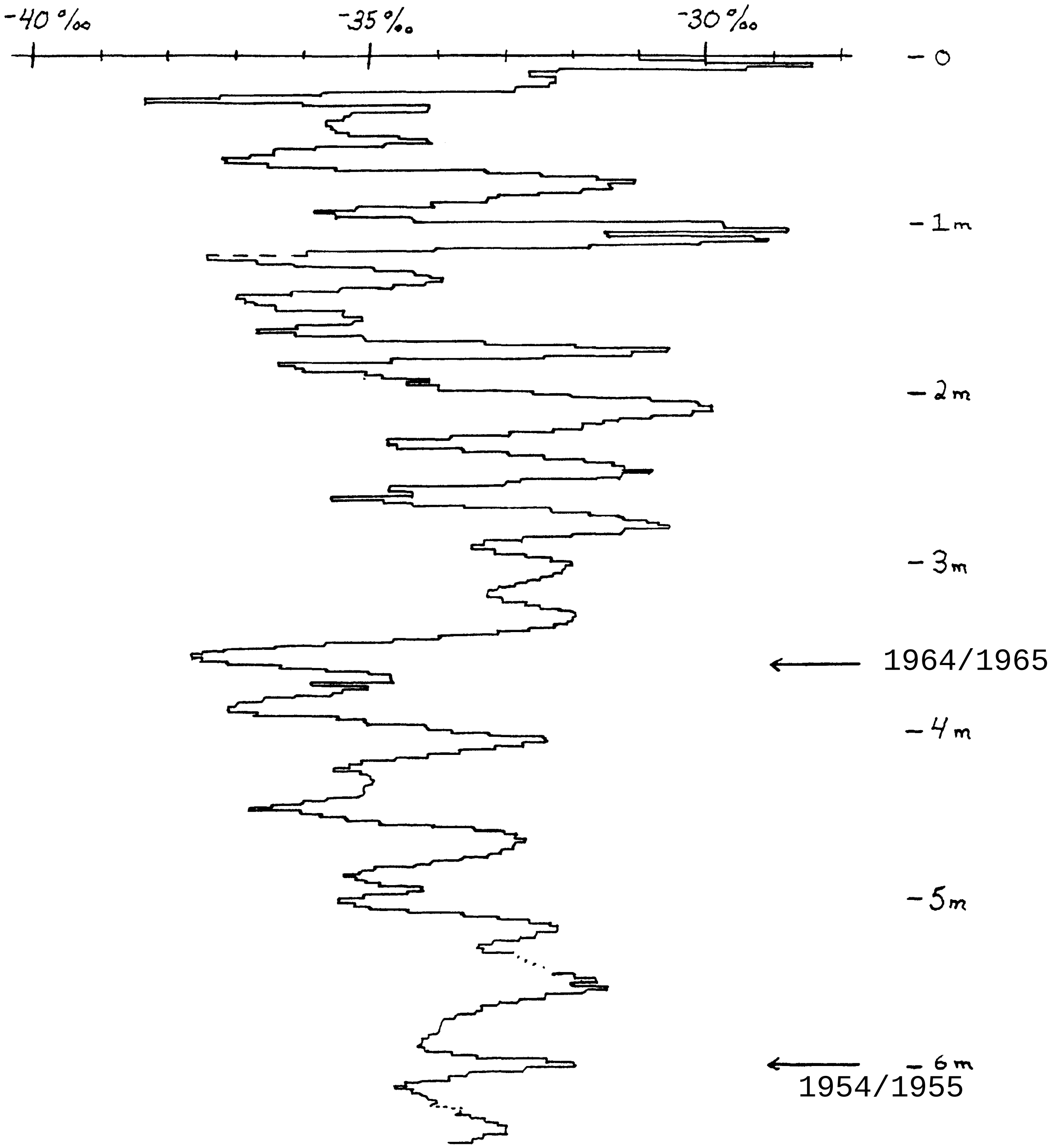

Figure 2. Profile of <u>Pit 2803</u>

Mean = -33.8054 $\pm$ .0425 $^{o}/_{oo}$

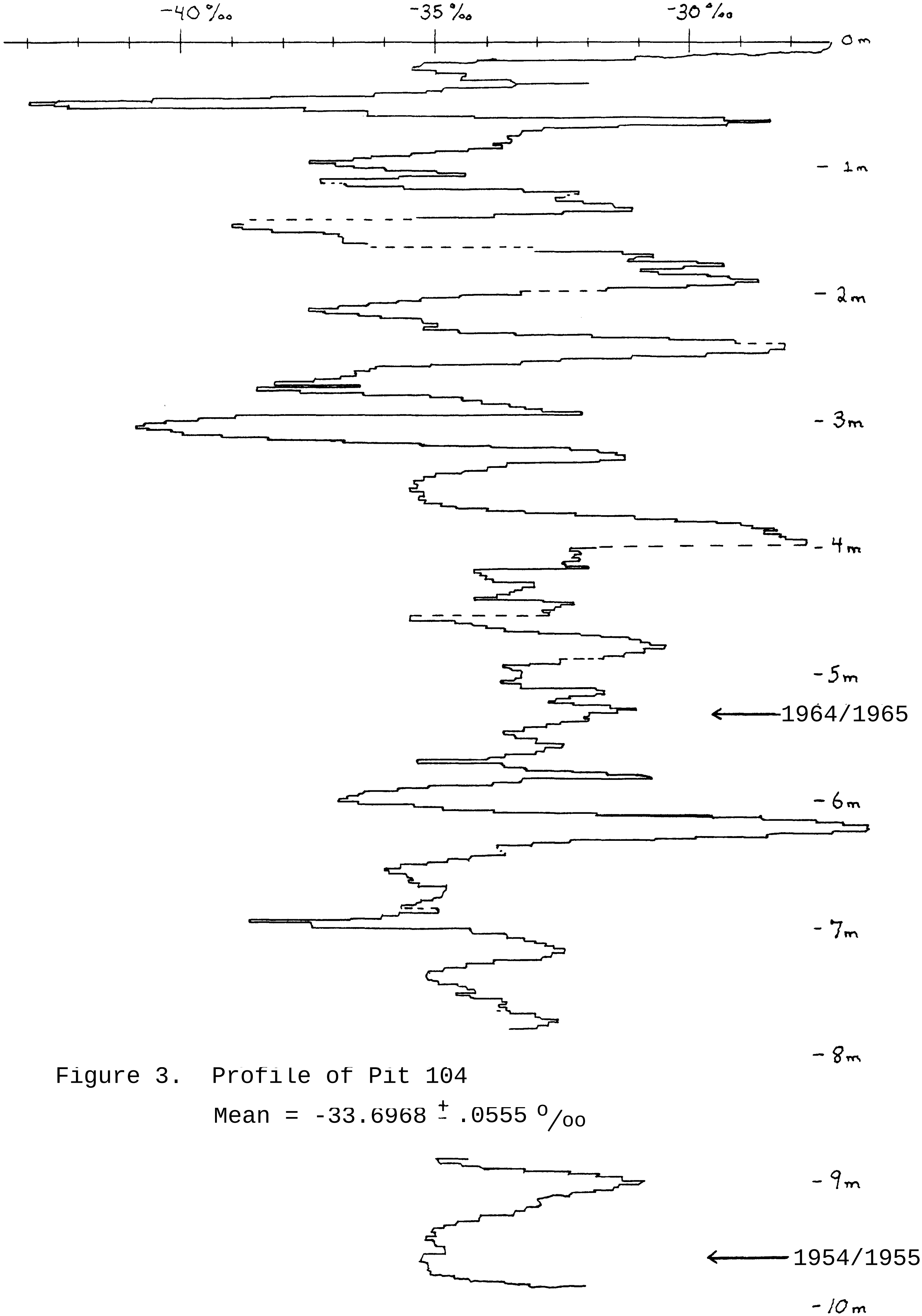

Figure 3. Profile of Pit 104

Mean = -33.6968 ± .0555 $^{o}/_{oo}$

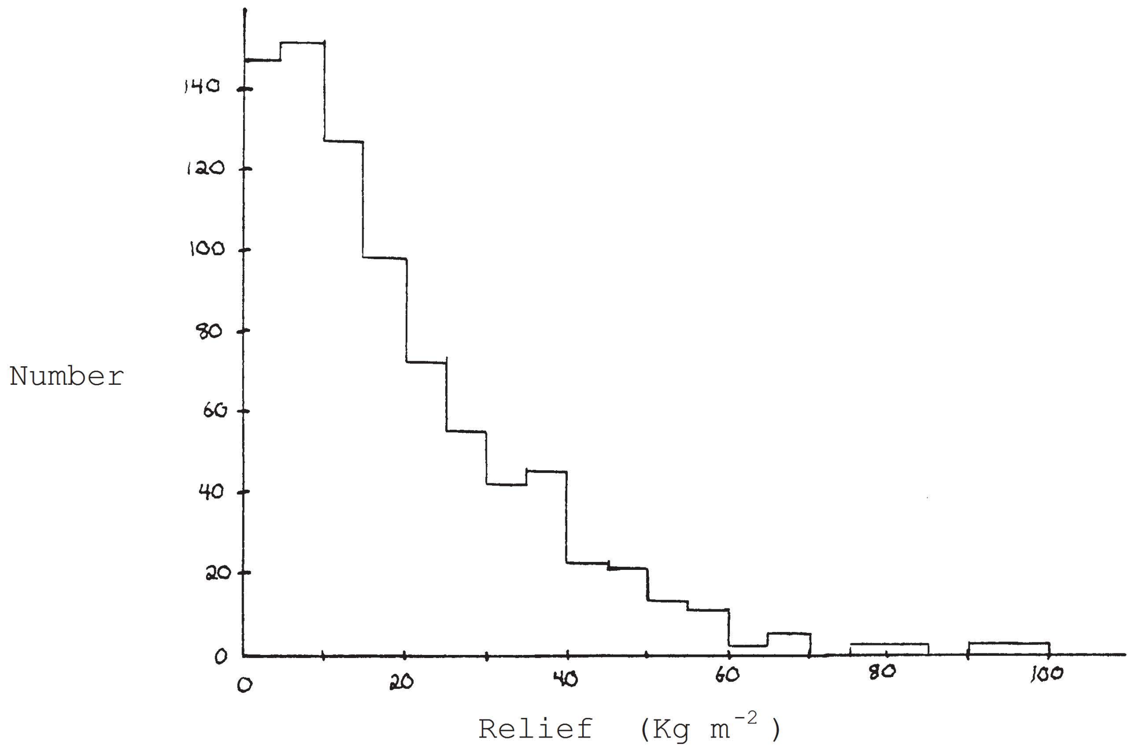

Figure 4. The Probability Distribution of Cut and Fill Features near Byrd Station, Antarctica. This can be converted to relief in centimeters by dividing the relief by 3Kg/m^2cm. Total sample size was 824 points. (Adapted from Surface Mass Balance Variability near Byrd Station,Antarctica, and its Importance to Ice Core Stratigraphy by I.M. Whillans)

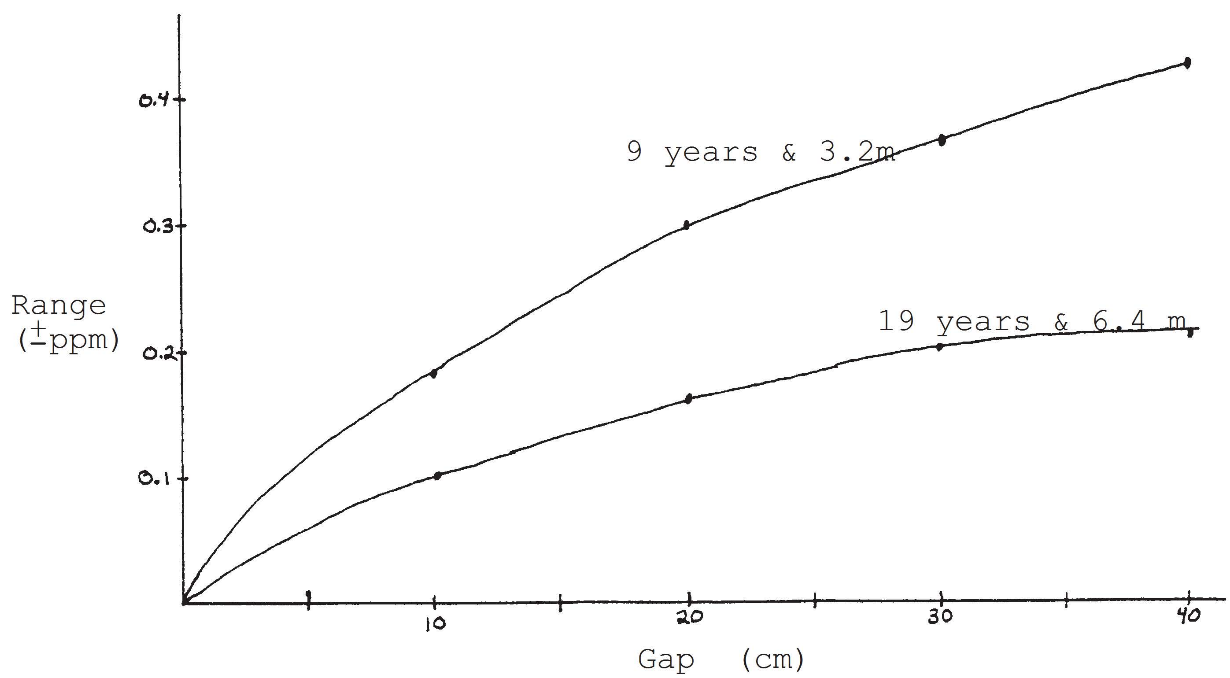

Figure 5. <u>Pit 2003</u>
Accumulation Rate= 166 Kg/m^2yr ; Mean = -33.9346 ppm;
Avg. Range (9)= $\pm$ 0.1364 ; Avg. Range (19) = $\pm$ 0.0694

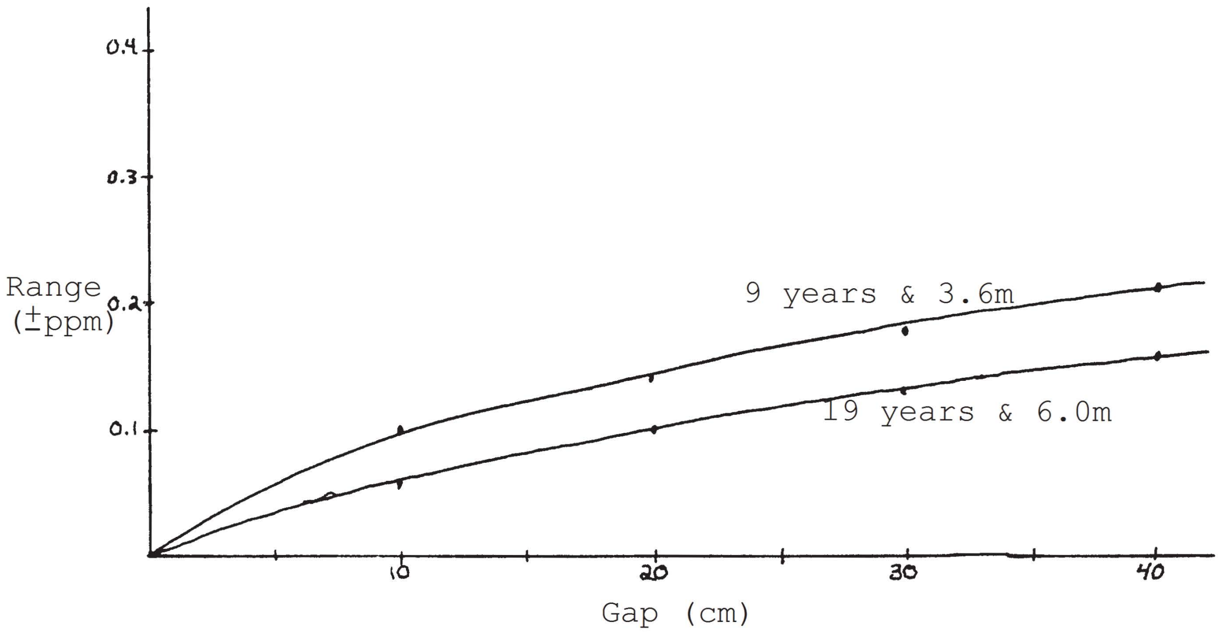

Figure 6. Pit 2803
Accumulation Rate= 133 Kg/m^{2}yr ; Mean = -33.8054 ppm
Avg. Range (9) = ±0.0716 ; Avg. Range (19)= ±0.0425

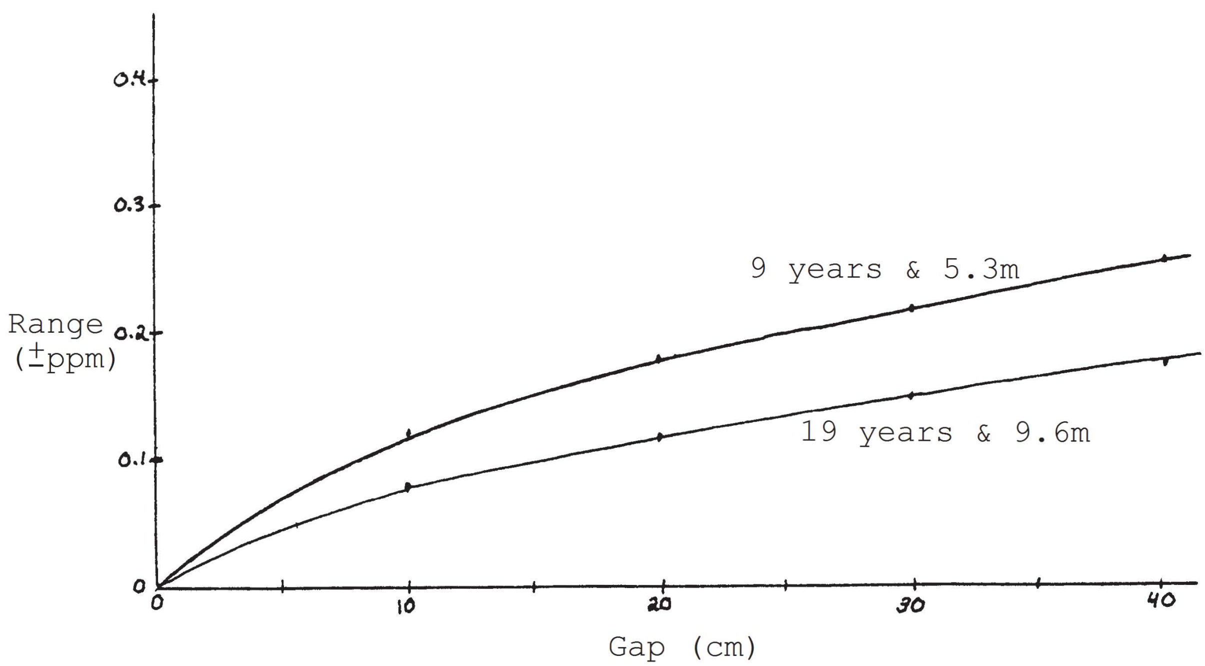

Figure 7. Pit 104
Accumulation Rate= 227 Kg/m^{2}yr ; Mean = -33.6968ppm;
Avg. Range (9) = ±0.0921 ; Avg. Range (19)= ±0.0555

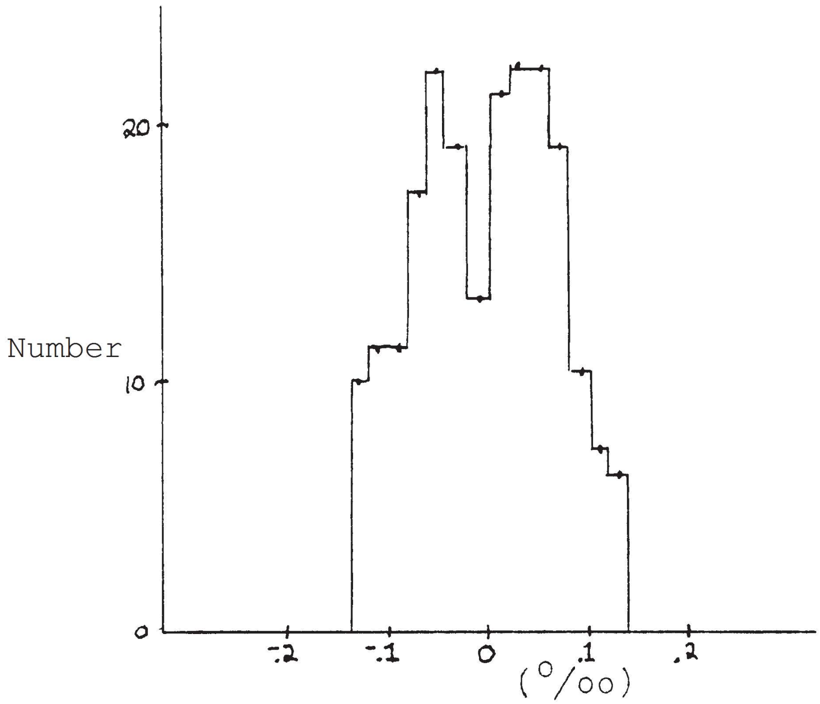

Figure 8a. Plot of Range Distribution for Pit 2803 with 20 cm gap
Range$_{20}$ = $\pm$0.14 °/oo

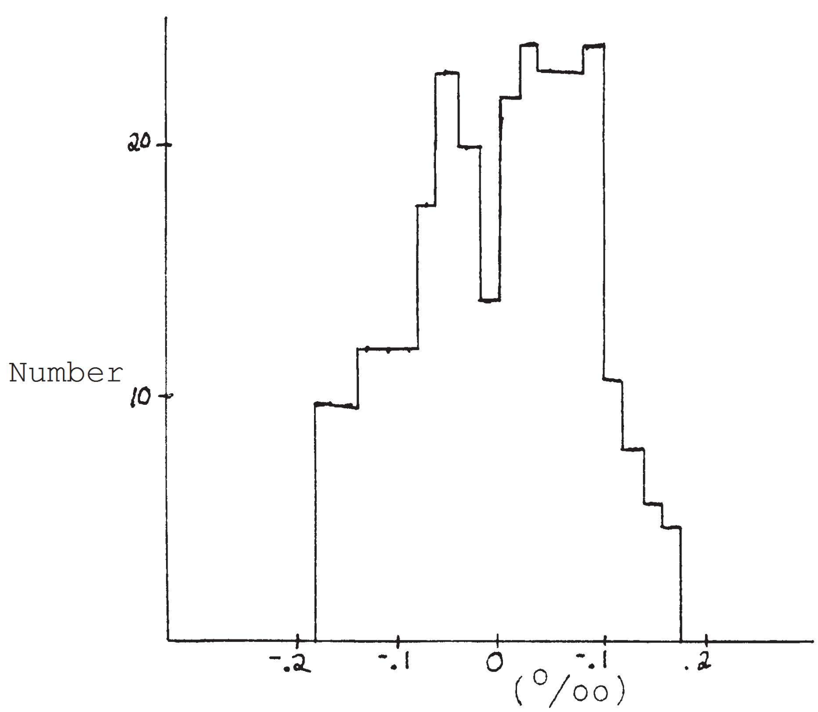

Figure 8b. Plot of Range Distribution for Pit 2803 with 30 cm gap

Range$_{30}$ = $\pm$0.18 °/oo

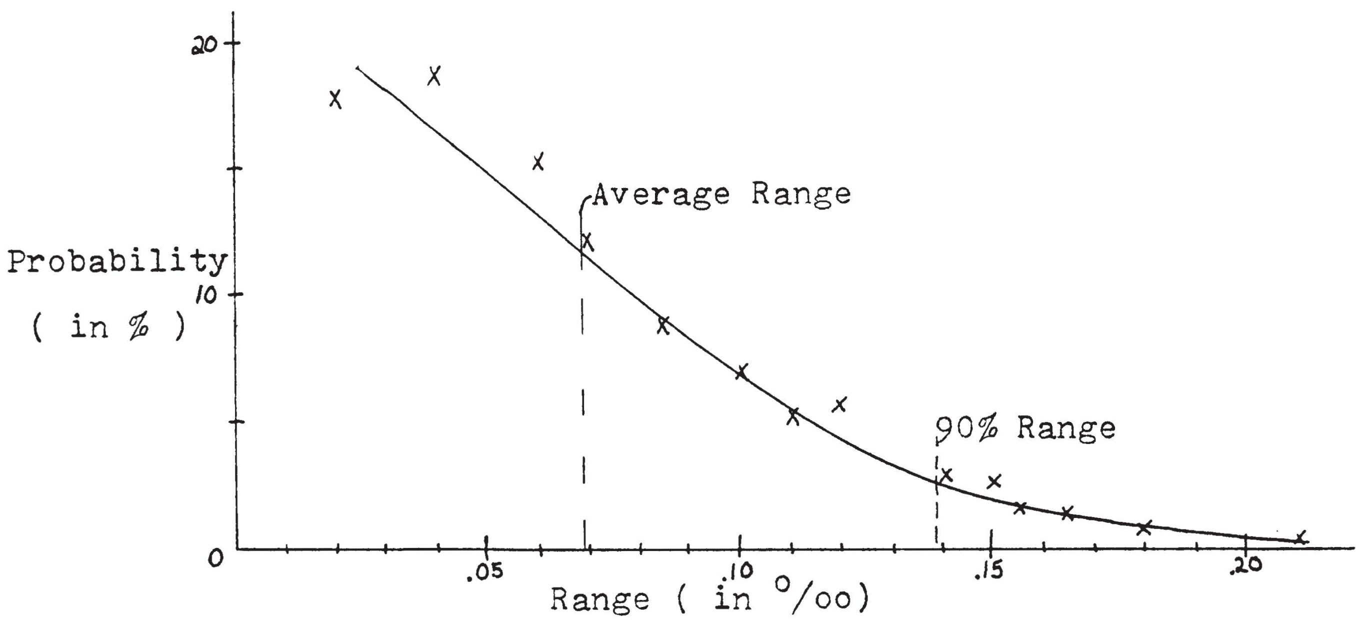

Figure 9. Range-Probability Curve for <u>Pit 2003</u>

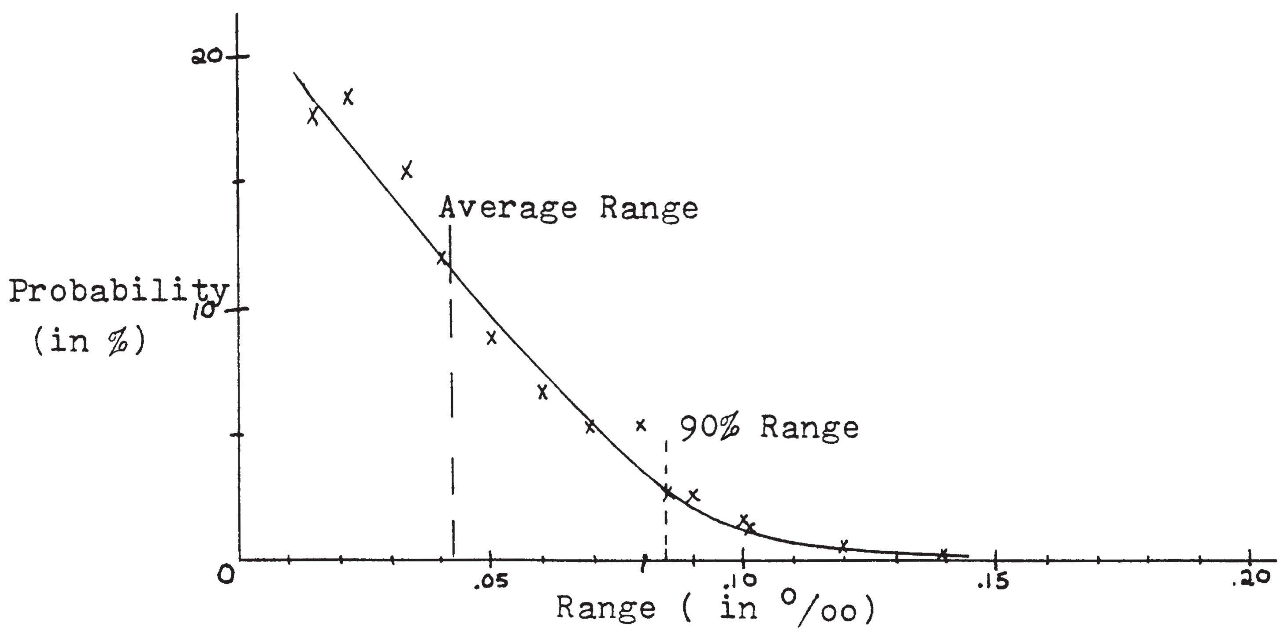

Figure 10. Range-Probability Curve for <u>Pit 2803</u>

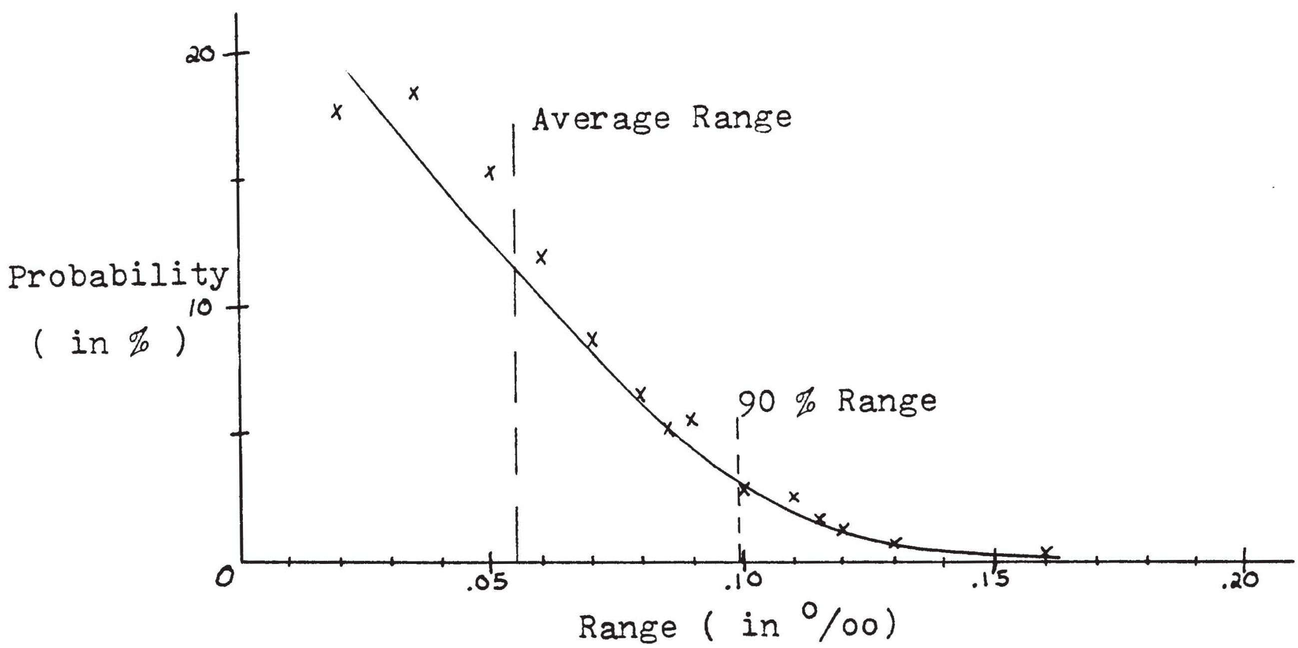

Figure 11. Range-Probability Curve for Pit 104

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